# Adaptive Modified Minimally Switched Hysteresis Controlled Shunt Active Power Filter for Harmonic Mitigation

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***Abstract*— The main focus of this article is to investigate the effects of Adaptive control on the switching frequency and Total Harmonic Distortion of a modified, minimally switched hysteresis controlled shunt active power filter. Reference current generation was done using Instantaneous real and reactive power algorithm. Pulses to the minimally switched grid interactive inverter in which only two switches are controlled at a time, had been generated using a modified hysteresis current controller. Use of Modified Hysteresis controller results in reducing the switching loses to one-third but results in increase in current THD than the conventional hysteresis controller. To overcome this, pulses to the modified hysteresis controller were generated employing adaptive control by modifying pulses from a conventional hysteresis controller. Using adaptive control instantaneous switching frequency was reduced and maintained nearly constant and THD was brought to the limits specified by the standards, thus overcoming the disadvantage of conventional and modified hysteresis controller which has variable switching frequency. A comparison of Modified Hysteresis controller with and without Adaptive control has been made, to show the reduction in THD. The system was simulated using MATLAB-SIMULINK.**

***Index Terms*— Adaptive control, Harmonics, Modified Hysteresis Controller, Power Quality, Shunt active power filter, Total Harmonic Distortion, Switching Losses.**

## I. Introduction

Proliferation of power electronic devices like single phase/ three phase inverters, rectifiers, cyclo converters etc has led to severe harmonic pollution of power system network. These power converters though very flexible, efficient and cheap, are highly nonlinear. They absorb harmonic currents and reactive power from utility supply [1]. Power quality problems cause waveform distortions which results in power factor reduction, increased R.M.S value of supply current, over heating of distribution transformers ,interference with communication lines, power loss and poor system efficiency [2],[3]. Distorted supply current distorts the supply voltage profile at the Point of Common Coupling (PCC) [1], [4]. This distorted voltage affects the nearby connected consumers [5].

Several power quality standards like IEEE 519-1992, EC61000-3-2, IEC1000-3-2, IEC1000-3-4 etc. define the allowable limit of distortions in voltage and current waveforms [6].

Devices for controlling harmonic distortion include in-line reactors, zig-zag transformers, passive filters, active filters etc. Traditional tuned passive filters are very cheap and effective for harmonic elimination but suffer from draw backs like fixed compensation, large size and resonance [3], [7]. Remarkable progress on analysis, design and cost effective solution of active filters was made in the past two decades [2],[8],[9],[10].

The concept of active power filters gave a new turn to harmonic and reactive power compensation [11]. Modern active filters are smaller in physical size, more flexible and have better performance than traditional passive filters. Active power filter mitigates harmonic components of different order simultaneously. The main aim behind the installation of active power filter is to compensate for current harmonics and imbalance [2]. Active power filter has two major parts ,a controller that generates the compensating signals and a three phase inverter for injecting the compensating currents into the grid.

Several time domain techniques like instantaneous reactive power algorithm [12], synchronous detection algorithm [13], unity power factor algorithm [14], synchronous frame based algorithm[15] Synchronous- flux detection algorithm [16] are used by researchers for the generation of reference currents of three phase shunt active filters. Recently IcosΦ algorithm was successfully employed for reference current generation [17].

Reference currents are compared with the actual filter currents for generation of gating pulses. Literature survey reveals that gating signals to the solid state switching devices of three phase inverter were synthesized using hysteresis control [18] , sliding mode control [19], adaptive control [20] [21], fuzzy logic control [22] Wavelet control [23], Energy shaping repetitive control [24] etc.

Hysteresis band current control method has wide acceptance because of quick current controllability, easy implementation, fast response and inherent peak current limiting capability. It does not require any information about system parameters. In conventional hysteresis controller switching frequency was not constant but varies with in a band. Increased inverter operating frequency helps in





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obtaining better compensating current waveform, but results in increased switching losses. So the range of frequencies selected should be a compromise between the inverter frequency and switching losses [20]. Compensation process also involves a Phase Locked Loop (PLL) synchronization and a PI controller for DC bus voltage regulation.

In the present paper the reference current was generated using instantaneous real and reactive power algorithm. Modified Hysteresis controller was used for the generation of switching pulses of the voltage source inverter. In modified hysteresis controller only 2 switches are controlled at high frequency at any instant of time [25]. The action of the controlled bridge in each 60 degree duration of line cycle is explained based on the polarity of source voltage and injected current. The pulses from the conventional controller were processed based on a switching algorithm to reduce the switching losses to one-third but it results in increase in current THD.

Variable switching frequency was another major problem with conventional and modified hysteresis controller. Adaptive hysteresis band current controller changes the hysteresis band width according to reference current to optimize switching frequency of inverter and THD of supply current [20]. Instantaneous switching frequency was reduced and maintained nearly constant using adaptive control and THD of supply current is brought to the limits specified by the standards.

The main focus of the paper is to investigate the effects of adaptive bandwidth on the THD of supply current and switching frequency of Voltage Source Inverter (VSI) based shunt active power filter with modified minimally switched hysteresis current controller. The work was simulated using MATLAB/SIMULINK. FFT analysis was done on source current waveform to validate that THD of source current waveform is within the five percent limit as specified by the standards.

## II. System Configuration

Voltage source inverter based shunt active power filter is discussed in this paper. It is connected in parallel with the harmonic producing loads at the Point Of Common Coupling (PCC). Configuration of shunt active power filter is shown in Fig.1 Shunt active power filter generates a current equal and opposite to that of harmonic current drawn by the load and injects it at the point of common coupling, making the source current sinusoidal. Filtering algorithm used and calculation of load current harmonics decides the characteristics of harmonic compensation. Current waveform for cancelling harmonics is achieved with Voltage Source Inverter (VSI) and interfacing inductor. Inductor provides smoothing and isolation for high frequency components.

Desired current waveform or actual filter current is obtained by controlling the switching of semiconductor switches in inverter. Control of wave shape is limited by switching frequency of inverter and available driving voltage across interfacing inductance.

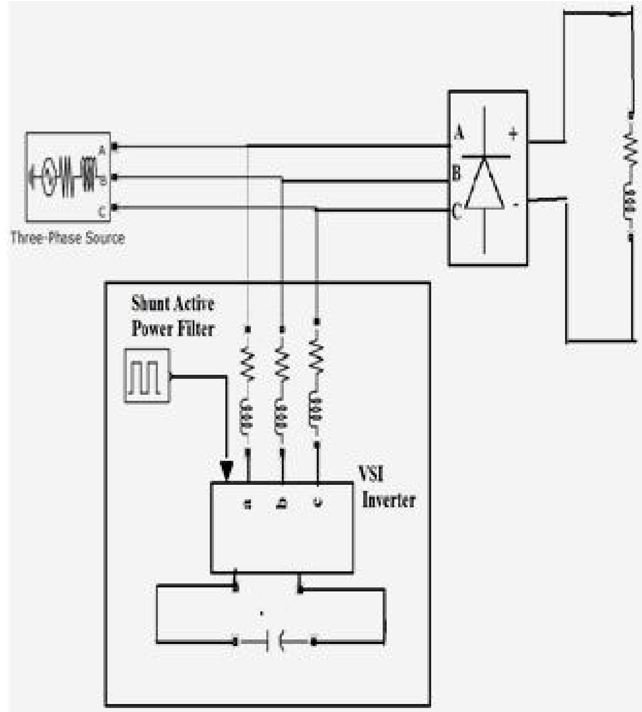


Figure 1.Shunt Active Power Filter

## III. Reference Current Generation Using Real And Reactive Power Algorithm

The instantaneous real and reactive power theory was employed for generation of reference current. It is based on the Clarke transformation of three phase voltages and currents into α-β coordinates [26]. The conversion of three-phase voltages and currents into α-β coordinates are given by

$$\begin{bmatrix} V_\alpha(t) \\ V_\beta(t) \end{bmatrix} = \sqrt{2/3}\begin{bmatrix} 1 & -1/2 & -1/2 \\ 0 & -\sqrt{3}/2 & -\sqrt{3}/2 \end{bmatrix}\begin{bmatrix} V_a \\ V_b \\ V_c \end{bmatrix} \tag{1}$$

Where Va, ,Vb and Vc are the three line voltages and Vα(t) and Vβ(t) are the voltages in α-β coordinates.

$$\begin{bmatrix} I_\alpha(t) \\ I_\beta(t) \end{bmatrix} = \sqrt{2/3}\begin{bmatrix} 1 & -1/2 & -1/2 \\ 0 & \sqrt{3}/2 & -\sqrt{3}/2 \end{bmatrix}\begin{bmatrix} I_a \\ I_b \\ I_c \end{bmatrix} \tag{2}$$

Where $I_a$ ,$I_b$ and $I_c$ are the load currents and $I_\alpha(t)$ and $I_\beta(t)$ are the currents in α-β coordinates.

According to instantaneous real and reactive power theory, real power p(t) and imaginary power q(t) is given by Eq.3

$$\begin{bmatrix} p(t) \\ q(t) \end{bmatrix} = \begin{bmatrix} V_\alpha & V_\beta \\ -V_\beta & V_\alpha \end{bmatrix}\begin{bmatrix} I_\alpha(t) \\ I_\beta(t) \end{bmatrix} \tag{3}$$

Reference compensation current for phase a, phase b and phase c is evaluated using Inverse Clarke's transformation



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using Eq.4.

$$\begin{bmatrix} I_a(t)^* \\ I_b(t)^* \\ I_c(t)^* \end{bmatrix} = \sqrt{2/3}\begin{bmatrix} 1 & 0 \\ -1/2 & \sqrt{3}/2 \\ -1/2 & -\sqrt{3}/2 \end{bmatrix}\begin{bmatrix} I_\alpha(t)^* \\ I_\beta(t)^* \end{bmatrix} \quad (4)$$

## IV. Synchronisation

Phase Locked Loop (PLL) tracks the phase of measured voltages Va , Vb and Vc Proper operation under balanced and unbalanced voltage conditions is ensured by PLL. Voltage fluctuations at the dc-bus capacitor was used to calculate extra power loss in inverter. Corresponding phase current amplitude calculated using a Proportional –Integral (PI) controller was multiplied with PLL output and added to reference compensation current in each phase. The losses in shunt active power filter was thus taken care of by three phase source and dc bus capacitor voltage becomes a self supporting on one.

## V. Conventional Hysteresis Controller With Adaptive Band

The purpose of the current controller is to control the actual filter current by forcing it to follow a reference current, thereby maintaining the current within the hysteresis band. The output signal from the hysteresis controller was used to activate the power switches of the grid interactive inverter. The switching logic for an inverter leg is given below

If IL < (ILref –HB), the upper switch is off and lower switch is on for the same leg.

If IL > (ILref + HB), the upper switch is on and lower switch is off for the same leg, where IL and ILref are the line reference currents respectively and IL is the actual filter current of the respective leg.

The fixed hysteresis band technique is very simple, easy to implement with robust current control performance, good stability, fast response and inherent ability to control peak current but suffers from variable switching frequency, heavy interference, harmonic content around switching side band and irregularity of the modulation pulse position. These drawbacks result in high current ripples and acoustic noise.

To overcome these undesirable drawbacks, this paper presents an adaptive hysteresis band control. The presented adaptive hysteresis band controller adjusts the hysteresis band width, according to the actual filter current. For adaptive control hysteresis bandwidth HB is given by

$$HB = \left\{ \frac{0.125U_{DC}}{f_c L}\left[1 - \frac{4L^2}{U_{DC}^2}\left(\frac{u_s}{L} + m^2\right)\right]\right\} \quad (5)$$

Where fc is modulation frequency, $m = di_c^{ref}/dt$ is the slope of reference current wave. UDC capacitor voltage of Voltage source inverter, L is the interface inductance, us is the voltage of respective phase. SIMULINK model for implementation of HB is shown in Fig.2. Adaptive hysteresis band method allows operating at nearly constant frequency. Adaptive hysteresis band current controller changes the hysteresis band width according to reference current to optimize switching frequency of inverter and THD of supply current [20].

## VI. Modified Hysteresis Controller With Adaptive Band

In a three wire system “Fig.3” it is sufficient to control current in only two phases. For compensating harmonic current at source side, harmonic current was injected into the grid from the inverter.

To inject harmonic current, a generalized switching algorithm was developed based on grid voltage and injected current polarities [25].Phases having same polarity of voltage was selected for control. This resulted in low rate of change of inductor current and hence easier control was possible. From the selected phases, controlling switches were selected based on the current polarity. Table.1 shows controlled and uncontrolled phases corresponding to different grid voltage regions. In 60°-120° region Va is positive, Vb and Vc are negative. B and C are the controlled phases and A is the uncontrolled phase. From the selected phases, controlling switches were selected based on the current polarity. Table.2 shows controlled and uncontrolled switches corresponding to 60°-120° grid voltage region. Table.3 shows controlled and uncontrolled switches corresponding to 240°-300° grid voltage region. Table.4 shows the design parameters. Comparison of Modified Hysteresis controller with and without adaptive control is shown in Table.5.

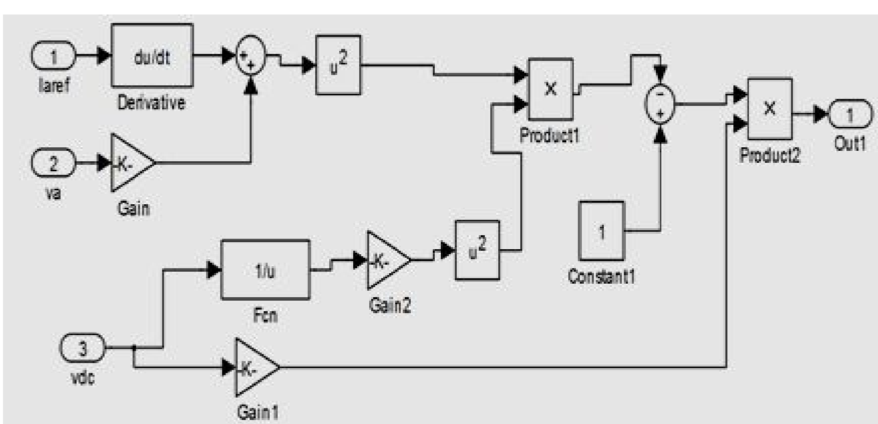


Figure 2. Simulink implementation of Adaptive Bandwidth




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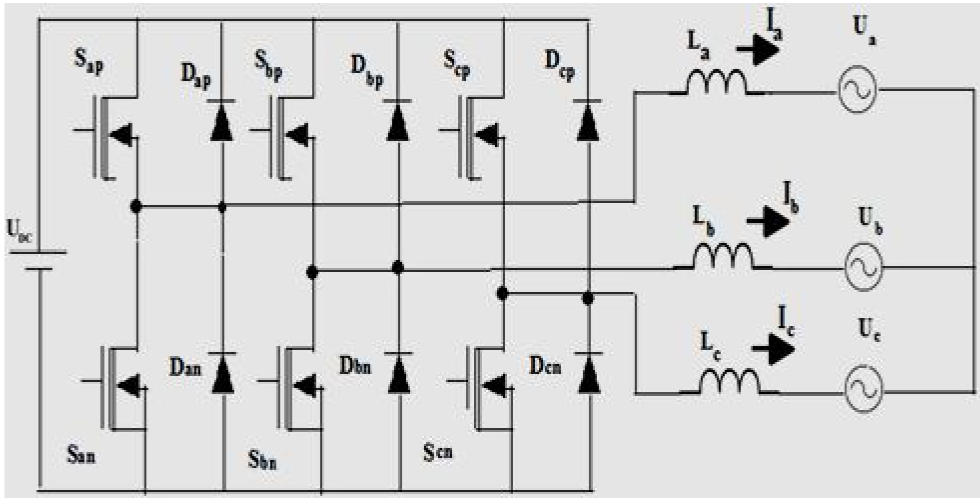


Figure 3. Three Phase Bridge Circuit

TABLE I. CONTROLLED AND UNCONTROLLED PHASES CORRESPONDING TO DIFFERENT GRID VOLTAGE REGIONS. IN 60°-120°

| Voltage sector | Ua | Ub | Uc | Controlled | Un controlled |
|---|---|---|---|---|---|
| 0-60 | +ve | -ve | +ve | A,C | B |
| 60-120 | +ve | -ve | -ve | B,C | A |
| 120-180 | +ve | +ve | -ve | A,B | C |
| 180-240 | +ve | +ve | -ve | A,C | B |
| 240-300 | -ve | +ve | +ve | B,C | A |
| 300-360 | -ve | -ve | +ve | A,B | C |

TABLE II. CONTROLLED AND UNCONTROLLED SWITCHES CORRESPONDING TO 60°-120° GRID VOLTAGE REGION

| Ia | Ib | Ic | Sap | Sbp | Scp | San | Sbn | Scn |
|---|---|---|---|---|---|---|---|---|
| +ve | -ve | -ve | On | | | | C | C |
| +ve | -ve | +ve | On | | C | | C | |
| +ve | +ve | -ve | On | C | | | | C |
| -ve | +ve | +ve | Off | C | C | | | |
| -ve | -ve | +ve | Off | | C | | C | |
| -ve | +ve | -ve | Off | C | | | | C |

TABLE III. CONTROLLED AND UNCONTROLLED SWITCHES CORRESPONDING TO 240°-300° GRID VOLTAGE REGION

| Ia | Ib | Ic | Sap | Sbp | Scp | San | Sbn | Scn |
|---|---|---|---|---|---|---|---|---|
| -ve | +ve | +ve | | C | C | on | | |
| -ve | +ve | -ve | | C | | on | | C |
| -ve | -ve | +ve | | | C | on | C | |
| +ve | +ve | -ve | | C | | off | | C |
| +ve | -ve | -ve | | | | off | C | C |
| +ve | -ve | +ve | | | C | off | C | |

## VII. SWITCHING ALGORITHM

Let t1, t2, t3, t4 t5, t6 represent the regions 0°-60°, 60°-120°,120°-180°, 180°-240°, 240°-300°,300°-360° the voltage sector respectively[25]. Let symbols Xa, Xb, Xc represent the polarity of reference currents Iaref, Ibref, Icref respectively. Boolean expressions formulated for enabling signals to switches Sap ,San ,Sbp ,Sbn, Scp, Scn in terms of t1, t2, t1, t3, t4, t5, t6 Xa, Xb, Xc are given below

TABLE IV. DESIGN PARAMETERS

| | |
|---|---|
| Source voltage | *415 V L-L* |
| system frequency | 50Hz |
| dc link voltage | 680 V |
| dc-bus capacitance | 5000micro farad |
| interfacing inductance | 1.5Mh |
| ac-side resistance | 1 ohm |
| Load | 1500W,1000VAR |
| bridge rectifier | Three phase diode rectifier |

TABLE V. COMPARISON OF MODIFIED HYSTERESIS CONTROLLER WITH AND WITHOUT ADAPTIVE CONTROL

| Controller Used | % Current THD | Optimized Inverter Frequency |
|---|---|---|
| Modified Hysteresis Controller Without Adaptive Control | 6.73% | 20Khz |
| Modified Hysteresis With Adaptive Control | 5.0% | 15.5Khz |

$$S_{ap}(c) = (t_1 + t_3 + t_4 + t_6)X_a \tag{6}$$

$$S_{ap}(on) = t_2 X_a \tag{7}$$

$$S_{ap} = S_{ap}(c)a_p + S_{ap}(on) \tag{8}$$

$$S_{an}(c) = (t_1 + t_3 + t_4 + t_6)X_{a'} \tag{9}$$

$$S_{an}(on) = t_5 X_{a'} \tag{10}$$

$$S_{an} = S_{an}(c)a_n + S_{an}(on) \tag{11}$$

Similar expressions can be obtained for Sbp, Sbn, Scp and Scn

## VIII. MATERIALS AND METHODS

Simulation was carried out to demonstrate the effectiveness of adaptive controlled modified hysteresis controller in shunt active power filtering to mitigate harmonics. The test system used to carry out the analysis in Fig.4 consists of a three phase voltage source and a three phase diode bridge rectifier with RL load. The active filter is


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connected to the test system through an interfacing inductor L. The values of the circuit elements used in the simulation are given in Table 4. MATLAB/SIMULINK is used to simulate the test system and the proposed shunt active filter is shown in Fig.5.

## IX. Simulation Results

The three phase source current and load current before compensation is shown in Fig.6. It can be seen that both are identical and highly non linear. MATLAB implementation of Adaptive control is shown in Fig.7. Fast Fourier Transform (FFT) analysis of Source current before compensation is shown in Fig.8. The THD of source current before compensation is found to be 29.4%. FFT analysis of Source current waveform after compensation with modified Hysteresis controller with adaptive properties is shown in Fig.9.

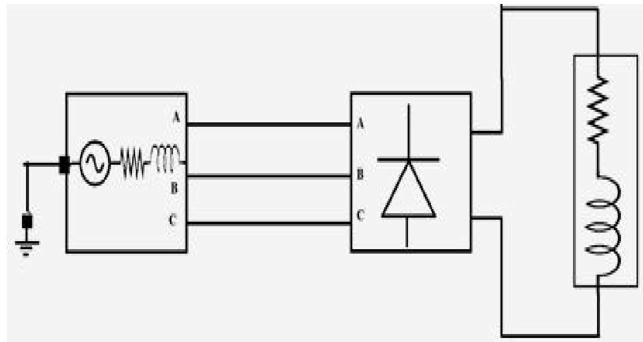


Figure 4. Test System

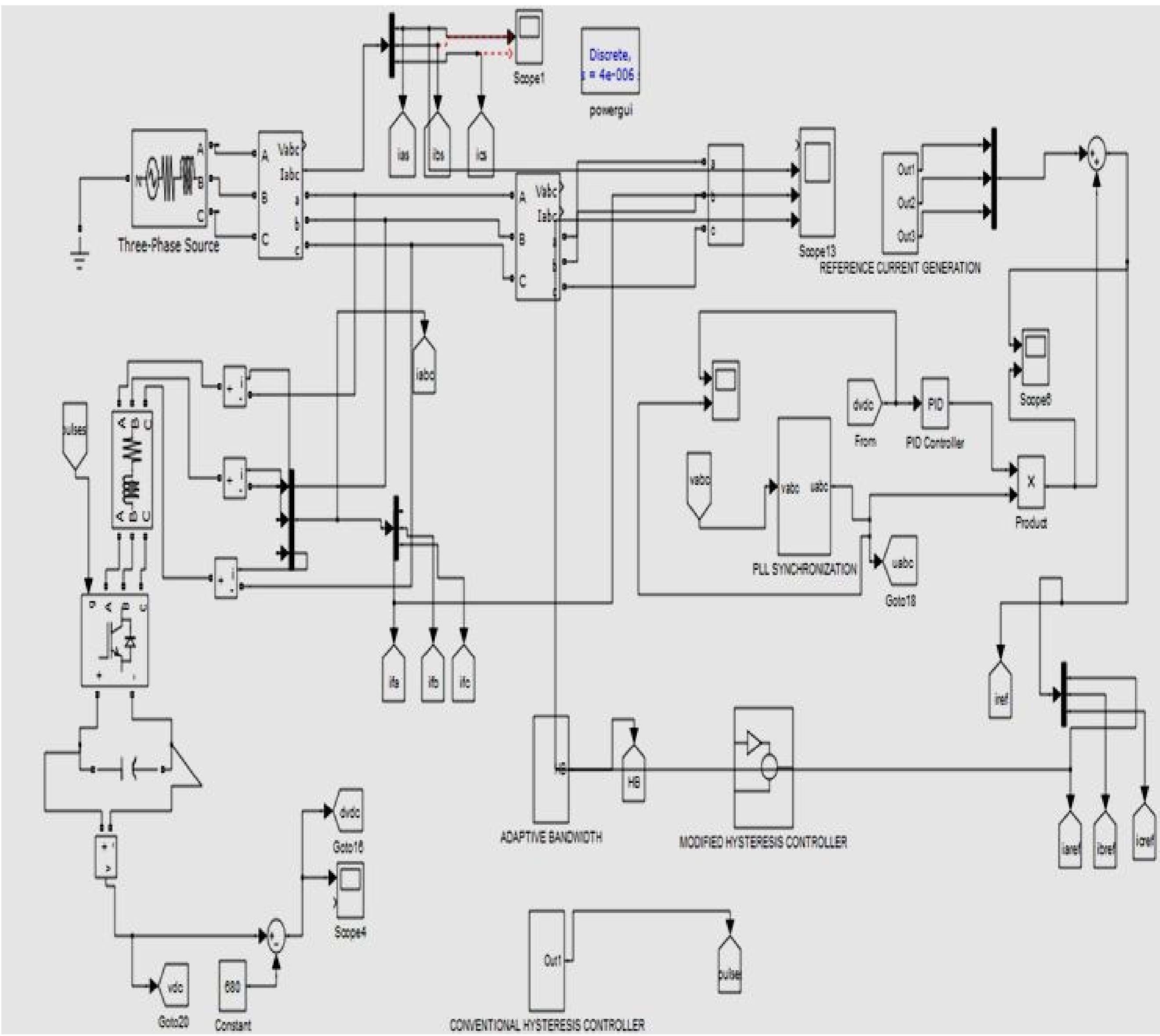


Figure 5. MATLAB Simulation

Total Harmonic distortion of source current after compensation was reduced to 5% which is well with in the specified limits It was inferred from Fig.10 that the losses in shunt active power filter was taken care of by three phase source and DC bus voltage becomes a self supporting one .The DC bus capacitor voltage was maintained at 680 Volts.





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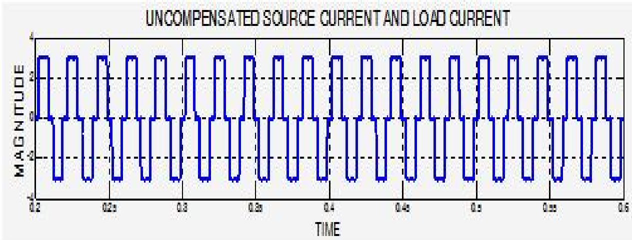


Figure 6. Nonlinear source current and load current

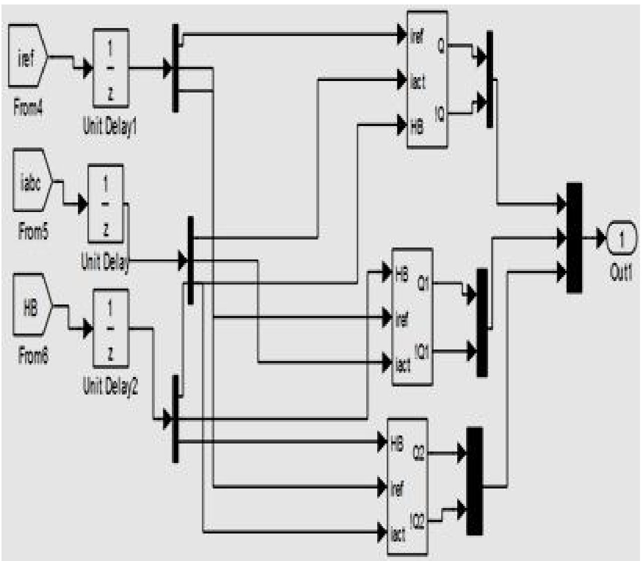


Figure 7.Implementation of Adaptive Control

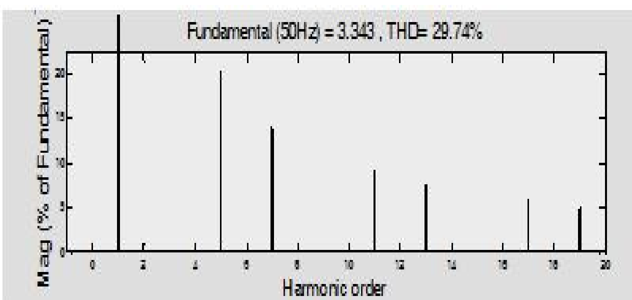


Figure 8.THD of uncompensated source current

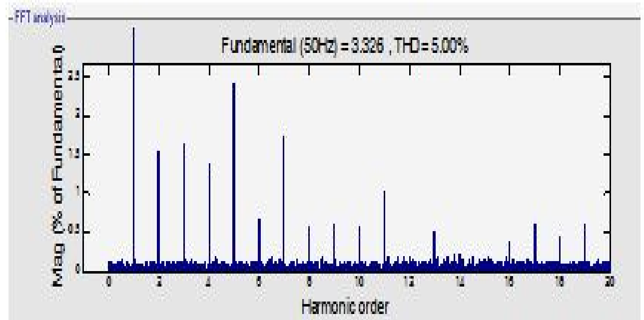


Figure 9.THD of Compensated source current

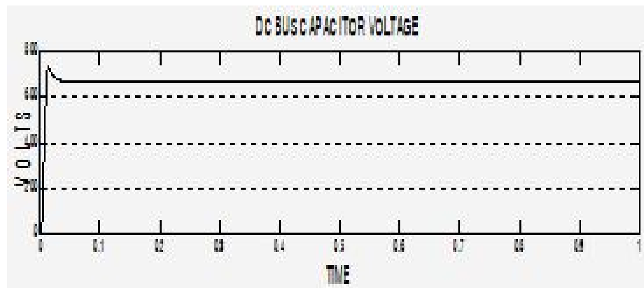


Figure 10. DC bus Capacitor Voltage

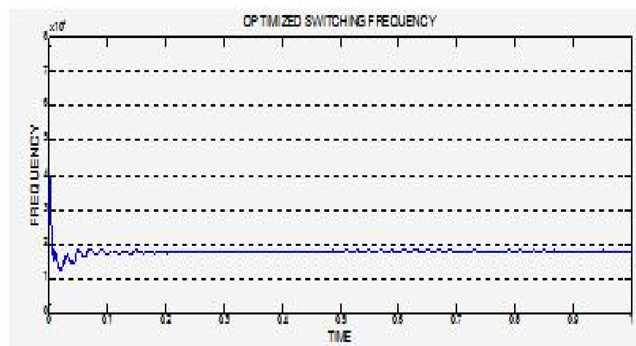


Figure 11.Optimized inverter Frequency

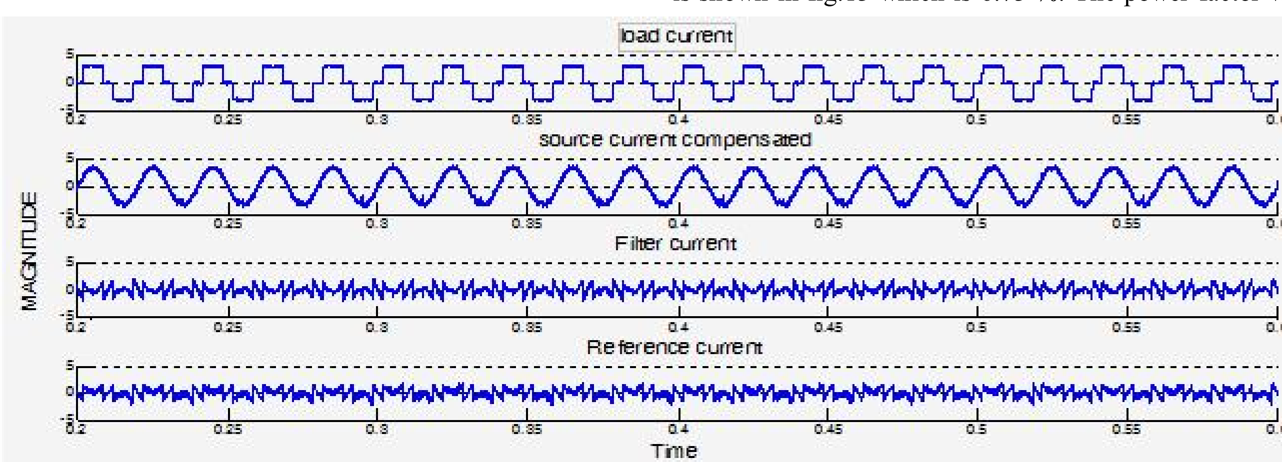


Figure 12. Load current, Compensated source current,reference current and filter current

Adaptive hysteresis band controller adjusts the hysteresis band width, according to the actual filter current. The switching frequency of the VSI inverter was nearly constant at 15.5kHz as shown in Fig.11. Fig.12. shows the compensated source current, load current, filter current and reference current waveforms. THD of source current without adaptive control is shown in fig.13 which is 6.73 %. The power factor was maintained nearly unity as shown in Fig.14.


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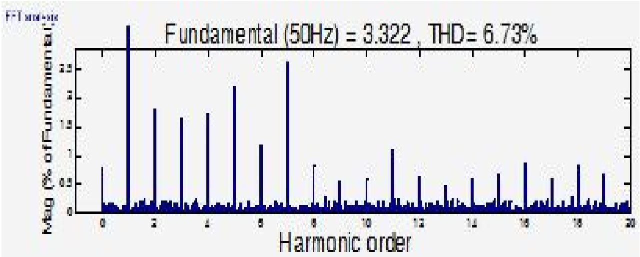


Figure 13.THD of source current without adaptive control

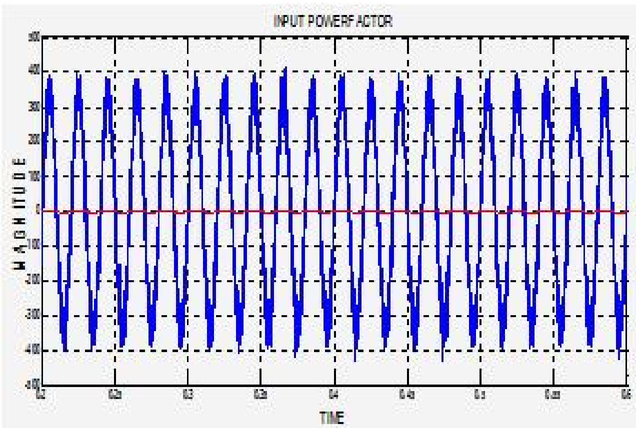


Figure 14. Input Powerfactor

## Conclusions

Modified hysteresis controller with adaptive control can be successfully employed for making the switching frequency of the voltage source inverter nearly constant thereby overcoming the disadvantage of conventional hysteresis controller which has variable switching frequency. By using modified hysteresis controller in which only two switches are controlled at any instant of time, ,the switching losses was reduced to one-third, but with an increase in THD of supply current. Adaptive control optimizes the switching frequency of the inverter and THD of source current, thereby reducing the switching losses further which would have been increased if high switching frequencies were used for the inverter.

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